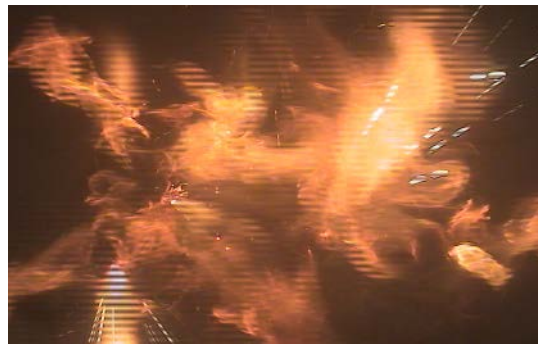
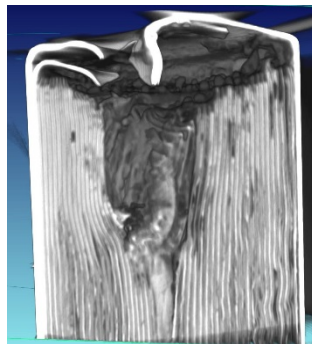
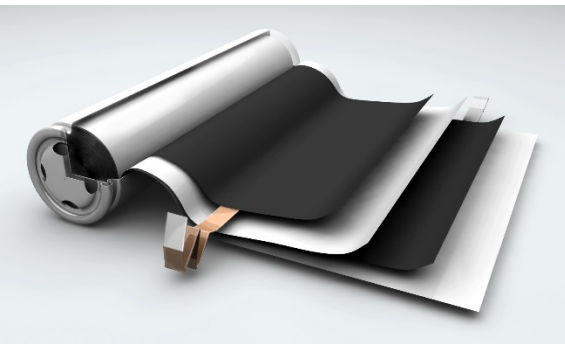


Exceptional service in the national interest



Battery Safety Testing

Leigh Anna M. Steele*, Josh Lamb, Chris Grosso, Jerry Quintana, Loraine Torres-Castro, June Stanley

Sandia National Laboratories

ES203

2017 Energy Storage Annual Merit Review

Washington, D. C. June 2017

This presentation does not contain any proprietary, confidential, or otherwise restricted information



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Overview

Timeline

- Start Date: Oct. 2016
- End date: Oct. 2017
- Percent complete: >75%

Budget

- FY17 Funding: \$1.3 M
- FY16 Funding: \$1.3M
- FY15 Funding: \$1.3M
- FY14 Funding: \$1.4M

Barriers

- Barriers addressed
 - Safety continues to be a barrier to widespread adoption
 - Understanding abuse response for a variety of cell types, battery chemistries, and designs
 - Failure propagation in battery systems limits inherent safety
 - Issues related to cell safety represent significant challenges to scaling up lithium-ion for transportation applications

Partners

- NREL, INL, ANL, ORNL
- USABC Contractors, USCAR, CAEBAT

Relevance and Objectives

Abuse tolerance evaluation of cells, batteries, and systems

- Provide independent abuse testing support for DOE and USABC
- Abuse testing of all deliverables in accordance with the USABC testing procedures
- Evaluate failure propagation in batteries
 - Impact of adding active thermal management material between cells
 - Alternative failure modes: mechanical and electrical
- Evaluation of short circuit currents in battery strings for various chemistries
- Alternative approaches to induce battery failures
- Provide testing data to support failure propagation model (NREL)
 - focus on alternative failure points, chemistries, and cell constructions
- Provide experimental support for mechanical modeling battery crash worthiness including dynamic testing development for CAEBAT
- Provide abuse testing support for ABR Post Test program (INL and ANL)
- Sandia abuse testing procedures to be detailed in a Sandia report

Milestones

Demonstrate improved abuse tolerant cells and report to DOE and the battery community

Milestone	Status
Complete Q1 USABC deliverables (NOHMS (1 st deliverables) and Amprius EV (1 st deliverables))	Q1-Q2
Complete Q2 USABC deliverables (LG Chem 12VSS)	Q1-Q2
Active thermal management analysis during propagation testing	Q2
Propagation testing with alternative initiation methods: overcharge	Q2
Internal short induced by IR laser	Q1-Q3
Analysis of short circuit current during failure propagation: battery chemistry comparison (LFP, LiCoOx, NCA, and NMC), design implications on propagation	Q2
Complete Q3 USABC deliverables (NOHMS (2 nd deliverables) and Maxwell modules: UCAP/li-ion)	Q3
T2M battery workshop: 2 nd Annual International Battery Safety Workshop May 9-10 th in Albuquerque	Q3
Development of dynamic testing for USCAR-CSWG/CAEBAT (drop tower drawings complete and building started in Q3)	Q4
Pouch cells used of short circuit current propagation studies	Q4
Complete Q4 USABC deliverables (Amprius 2 nd deliverables, Envia 12VSS, Maxwell UCAP pouch cells, NOHMS (3 rd deliverables), LG Chem EV)	Q4
Multi-cell pack testing to feed thermal propagation modeling	Q4



Milestone Complete

Approach and Capabilities

Cell and Module Testing Battery Abuse Testing Laboratory (BATLab)



Battery Pack/System Testing Thermal Test Complex (TTC) and Burnsite



Battery Calorimetry

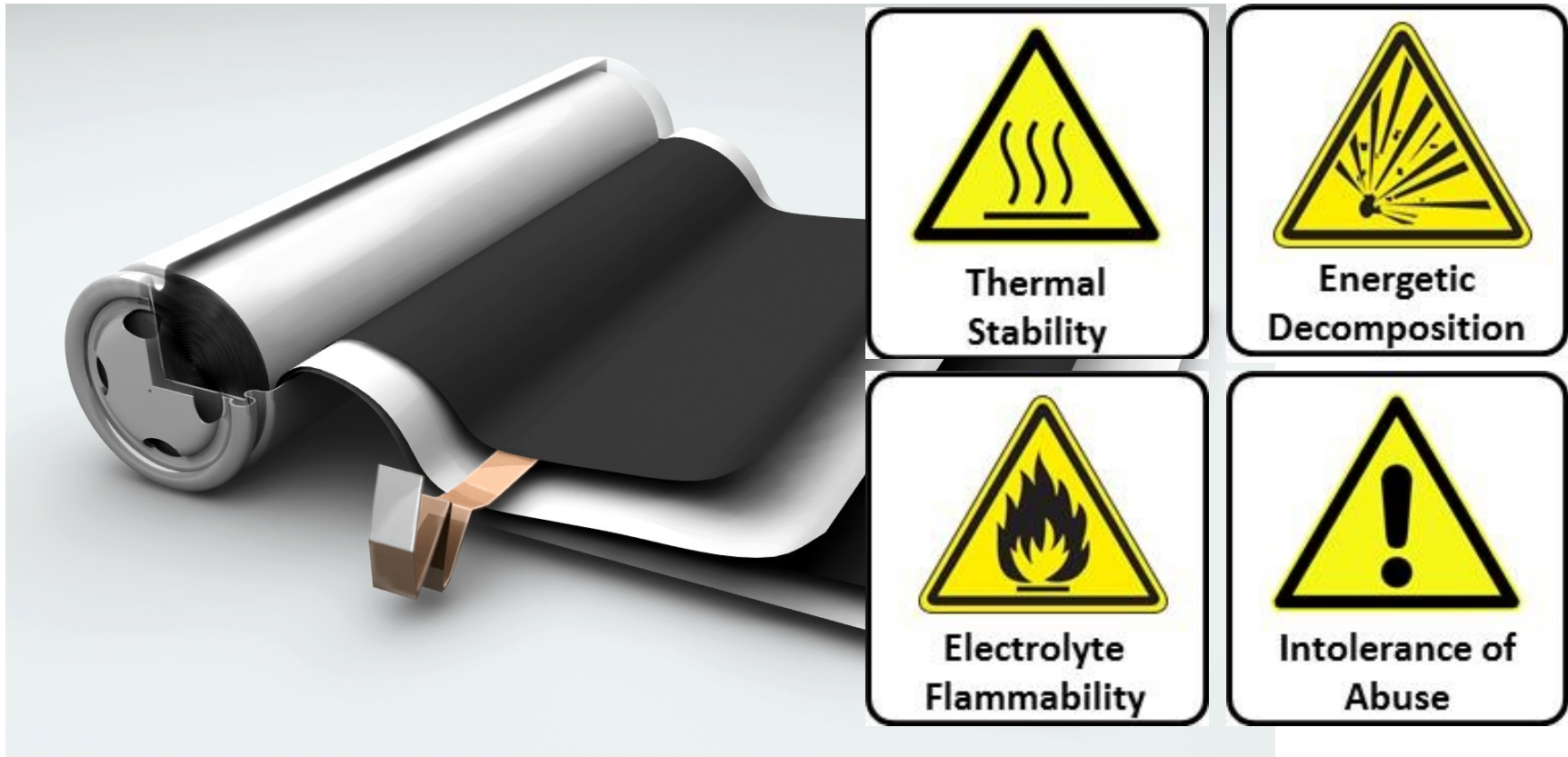


Technical Accomplishments/Progress/Results

Abuse Testing and Characterization:

- Completed testing of all USABC deliverables to date and reported results to the USABC TAC
- Stood up permanent large scale battery testing capability at Sandia's Burnsite and actively using site for USABC modules testing
- Current abuse testing procedures to be published as a Sandia report this FY
- Developed method to use a laser to induce a short within pouch cells
- Investigated propagation effects with alternative cell designs
 - Focus on pouch cell formats and active thermal management impacts
- Investigated alternative methods for failure propagation: overcharge
- Analyzed impact of battery chemistry and electrical connection on short circuit current between cells during failure propagation. Future work is to apply concept to alternative battery designs (pouch vs cylindrical) and report results
- Developed method for 3 point bend testing to support CAEBAT
- Completed design for dynamic drop testing: unit being built and will be housed at SNL remote site once complete
- Extended failure propagation modeling efforts with NREL using testing data
Provided testing support for several cell chemistry types (NMC, LFP, and Si) to varied levels of overcharge in support of the ABR post test program (ORNL, SNL, and ANL)
- T2M funds to host 2nd Annual IBSW in Albuquerque May 9-10th

Lithium-ion Safety Issues



Testing program aimed at understanding and improving abuse tolerance of energy storage systems

USABC Program Deliverables to SNL

Program	Deliverable
LGChem 12VSS	Cells (10) Q1/2
NOHMS	Cells (12 for first deliverable set) Q1/2
NOHMS	Cells (12 for second deliverable set) Q3/4
Envia	Cells (8) Q4
Amprius EV	Cells (10 for 1 st deliverable set) Q2
Amprius EV	Cells (10 for 2 st deliverable set) Q3/4
NOHMS	Cells (12 for 3 rd deliverable set) Q4
Envia EV	Cells (8) Q4
Maxwell 12VSS	Modules (2) Q3
Maxwell 12VSS	Ultracap pouch cells (4) Q4

Testing results for USABC are protected information

SNL Abuse Testing Procedures

SANDIA REPORT

SAND200X-XXXX
Unlimited Release
Printed Month and Year

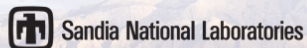
Sandia National Laboratories Rechargeable Energy Storage System (RESS) Abuse Testing Manual

Christopher J. Orendorff, Joshua Lamb, and Leigh Anna M. Steele

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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National Nuclear Security Administration under contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.



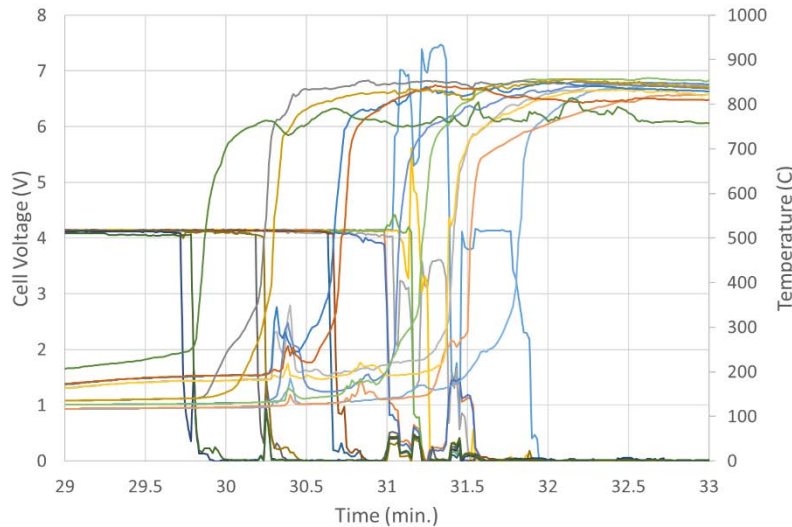
Notable changes:

- **Revision 2005 SNL Sandia Report (SAND2005-3123)**
- **Enhanced safety basis**
- **Updated to testing procedures according to current testing methods/capabilities**
- **Use of empirical data to support test conditions**
- **Failure propagation test**

- ***SNL revised abuse testing procedures to be published as a SAND report in Q4 for unlimited release***

Abuse Testing

Representative thermal abuse test of multi-cell COTS lithium-ion pouches (non-USABC)- 1kWh



- **Testing performed according to USABC Abuse Test Manual (heat 5°C/min to 250°C or failure)**
- **Usage of Burnsight for larger scale testing at SNL**
- **Complete propagation through 12 cell pack with burn time of ~ 5 min and peak temps of 800°C**

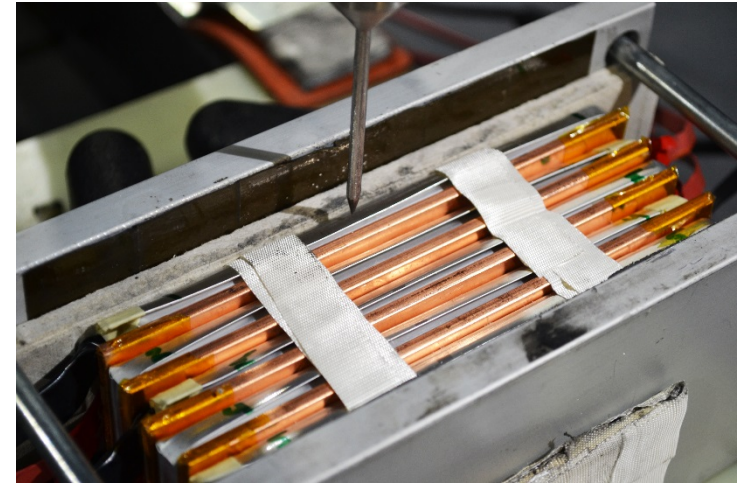
Failure Propagation Testing: Inclusion of Thermal Management

Methodology:

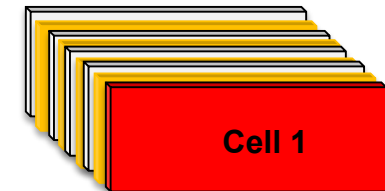
- Experimentally determine a reproducible thermal runaway initiator for each cell type
- Use this initiator to trigger a single cell thermal runaway failure in a battery
- Evaluate the propagation of that failure event

Experiment

- COTS LiCoO₂ 3Ah pouch cells
- 5 cells closely packed
- Failure initiated by a mechanical nail penetration along longitudinal axis of edge cell (cell 1)
- The current effort is focused on understanding extent of propagation with inclusion of passive thermal management in the form of heat sinks between pouch cells (aluminum and copper)



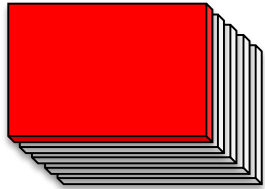
5 cell pack with aluminum or copper spacers between cells



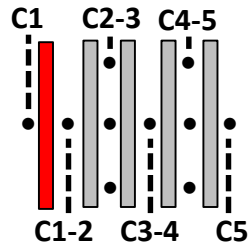
Failure Propagation: No Thermal Management

Failures initiated by mechanical insult to edge cell of COTS LiCoO₂ packs (3Ah cells)

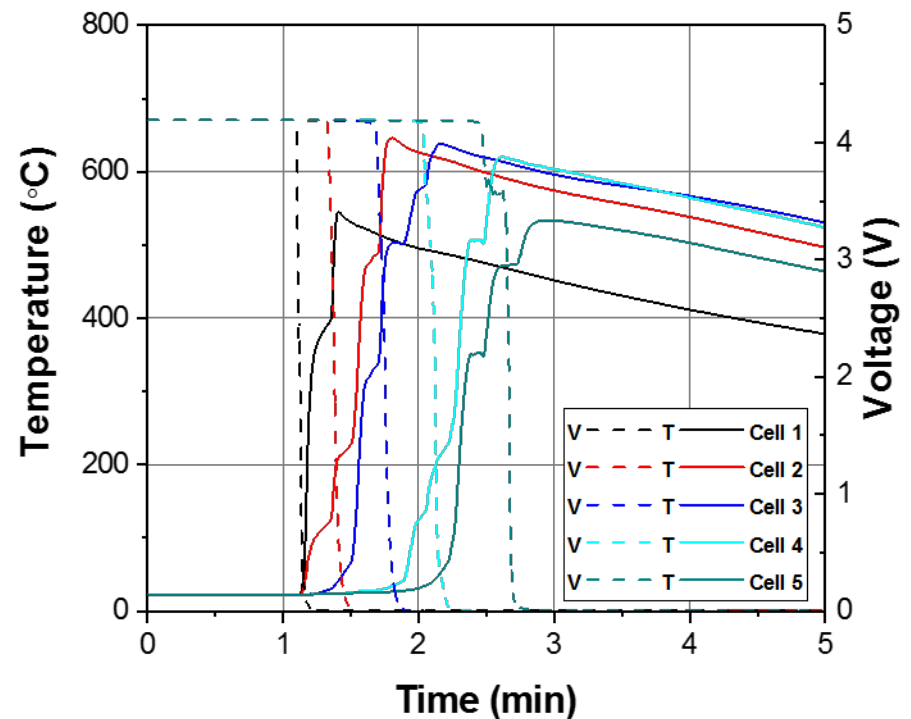
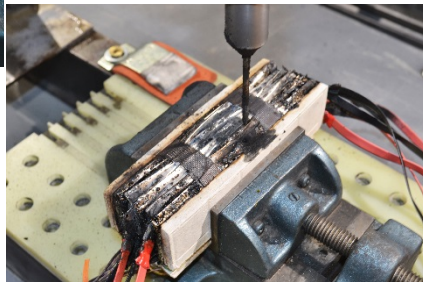
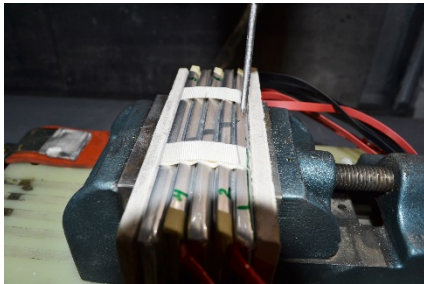
5 cell Battery



TC layout



- Successful initiation at Cell #1
- Propagation to adjacent cells
- Cascading failure to entire battery over 60 s

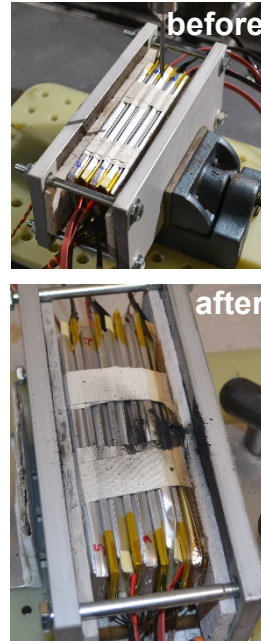
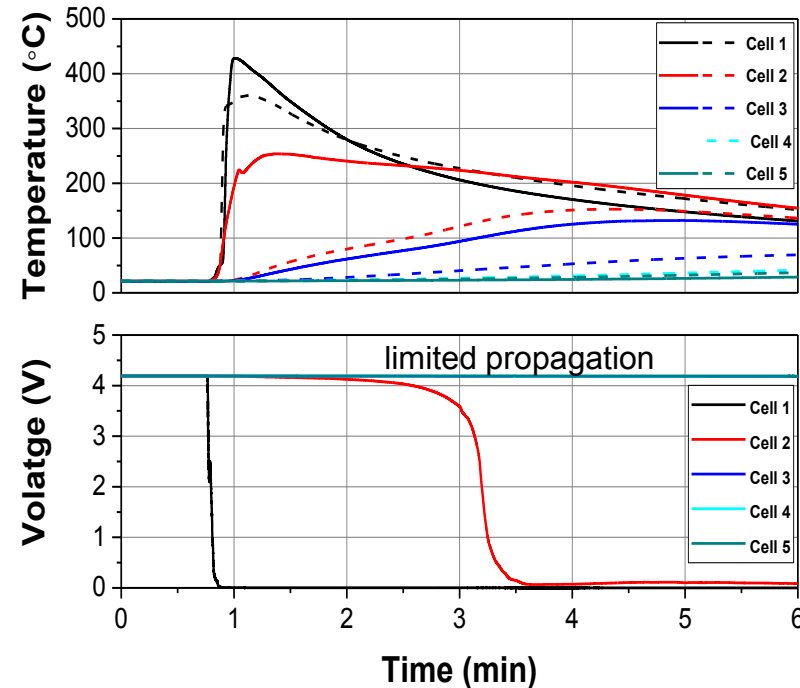


- *Observed complete propagation when cell are close packed with no thermal management*

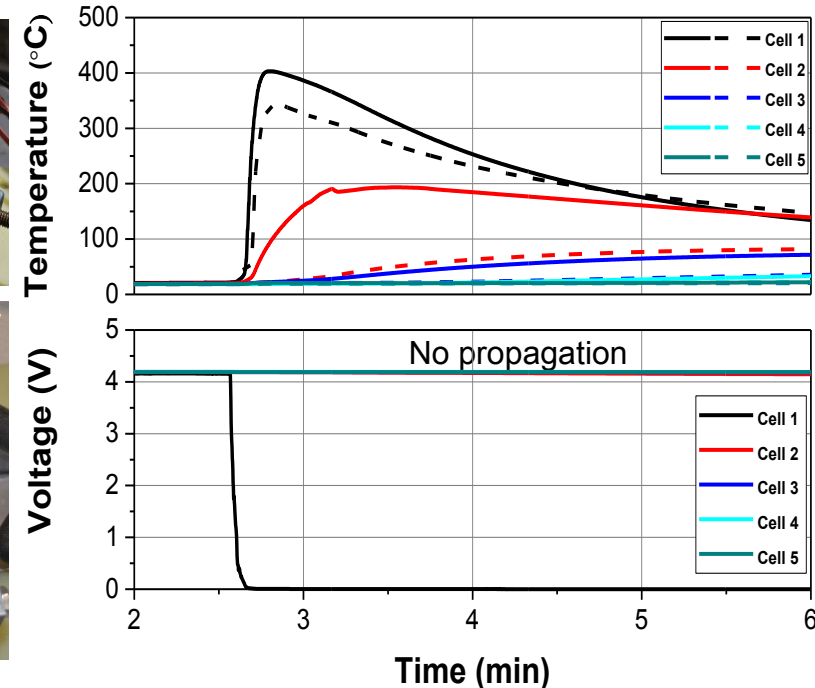
Failure Propagation: Aluminum spacer

Failures initiated by mechanical insult to edge cell of COTS LiCoO₂ packs

LiCoO₂ – 1/16" thick spacers



LiCoO₂ – 1/8" thick spacers

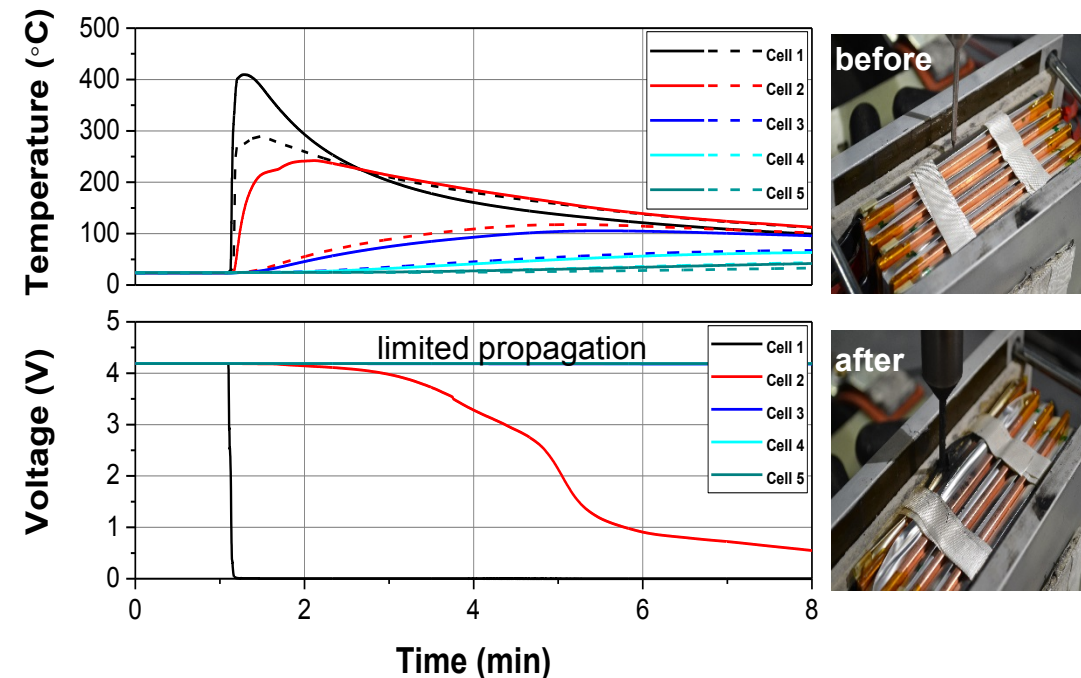


- Addition of aluminum spacers cut to the size of 3 Ah COTS cells was achieved
- Failure of cell 1 in both cases were consistent and peak temperatures reached ~400 °C
- Limited propagation (from cell 1 to 2) occurred with the thinner material (1/16")
- No propagation was realized when space thickness was increased to 1/8"

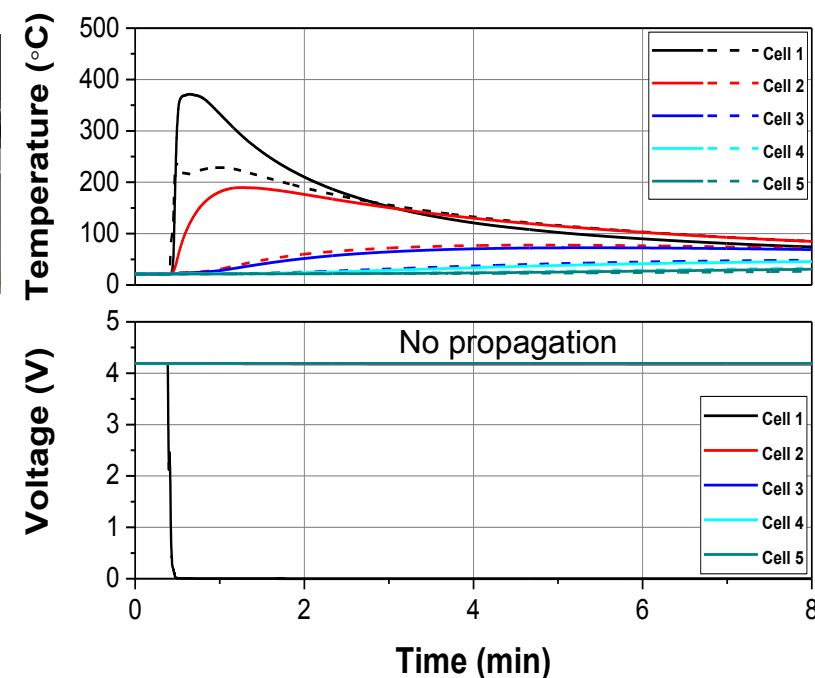
Failure Propagation: Copper spacer

Failures initiated by mechanical insult to edge cell of COTS LiCoO₂ packs

LiCoO₂ – 1/16" thick spacers



LiCoO₂ – 1/8" thick spacers

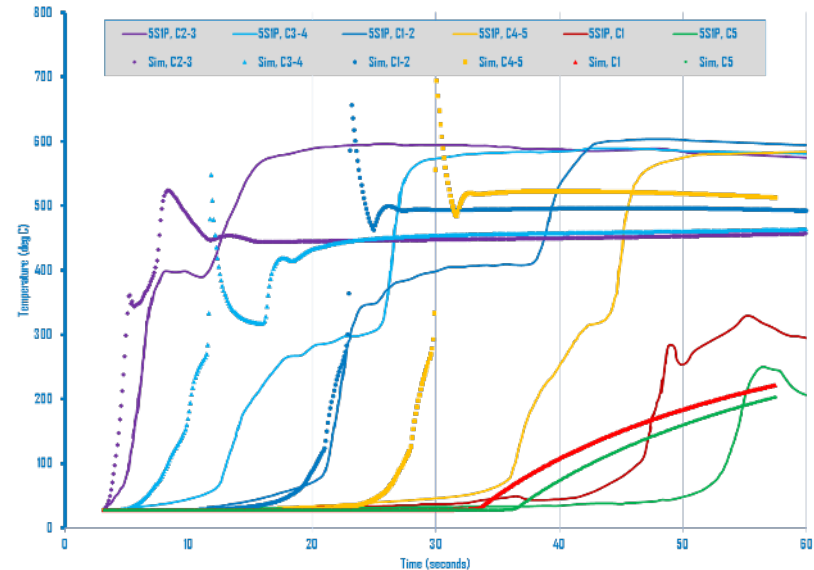
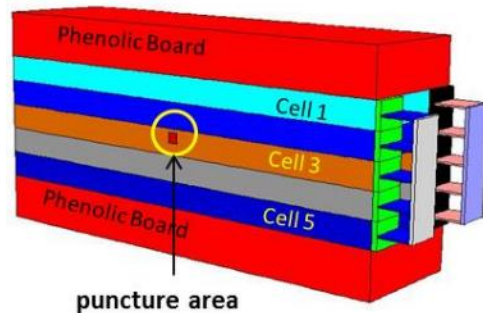


- *Addition of copper spacers cut to the size of 3 Ah COTS cells was achieved for comparisons of spacer size and material (Al vs Cu)*
- *Failure of cell 1 in all cases were consistent and peak temperatures reached ~400 °C*
- *Limited propagation (from cell 1 to 2) occurred with the thinner material (1/16")*
- *No propagation was realized when space thickness was increased to 1/8"*

Failure Propagation Model (NREL)

NREL electro-thermal and abuse model using lumped cell materials properties

LiCoO₂ Pouch Cell - 1S5P



Good agreement in the initial simulations with experiments with some deviation in the long duration events likely due to electrical or connectivity changes within battery over time during the failure event

Road map for follow on work looking at failure propagation modeling :

SNL provides testing data for the following Q3 and evaluate model in Q4

- (1) SNL to provide ARC and single cell thermal runaway data of 3Ah cells to help characterize electrochemical behavior
- (2) Alternative failure points in pack (center cell vs edge cell in 5 cell string)
- (3) Failure with thermal management: Al or Copper plates of various thickness
- (4) Failure at different states of charge

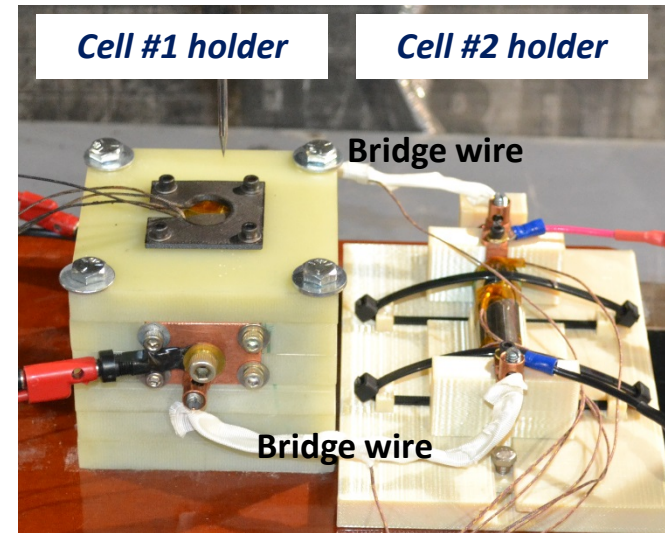
Short Circuit Current During Failure Propagation: Chemistry Comparison

Methodology:

- Use mechanical nail penetration along longitudinal axis to initiate thermal runaway in cell #1
- Develop fixturing to enable short circuit evaluation
- Evaluate the short circuit current between initiation point and cells in parallel

Experiment

- Cells electrically connected by constantan wire of known resistance
- FY16 focused on COTS LiCoO₂ 18650 and LFP 18650 and 26650 cells in 1S2P configurations
- FY17 focused on improving *robustness of fixturing* and *alternative chemistries for comparison*: COTS NCA and NMC 18650 cells in 1S2P configurations
- Focused on evaluation of the short circuit current when cell #1 undergoes a runaway event

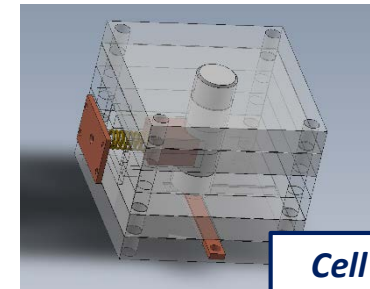


1S2P Battery: Constantan bridge wire connecting cells. Failure initiation point at Cell #1

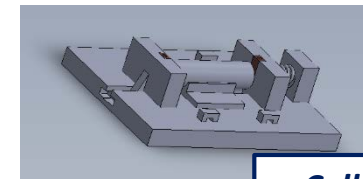
Short Circuit Current During Failure Propagation: Robustness of Electrical Connections

- Failures initiated by mechanical insult to cell 1 which is connected to cell 2 through constantan bridge wire
- Development of new testing fixture to increase reproducibility in FY16 (right)
- Additional effort to maintain electrical connection with cell 1 after runaway event
 - Use of spring on nail to apply opposing force keeping cell from ejecting after runaway (images below)

Testing Apparatus

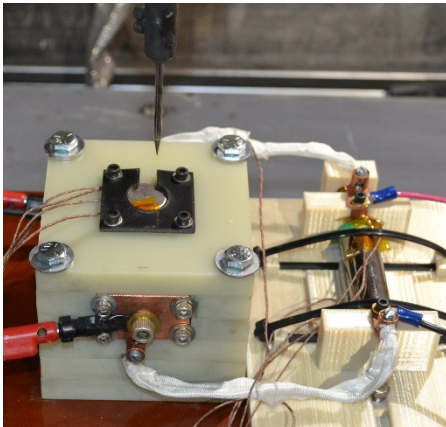


Cell #1 holder

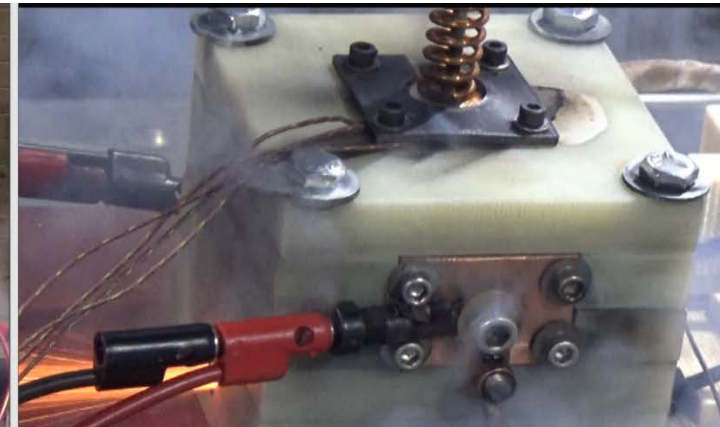
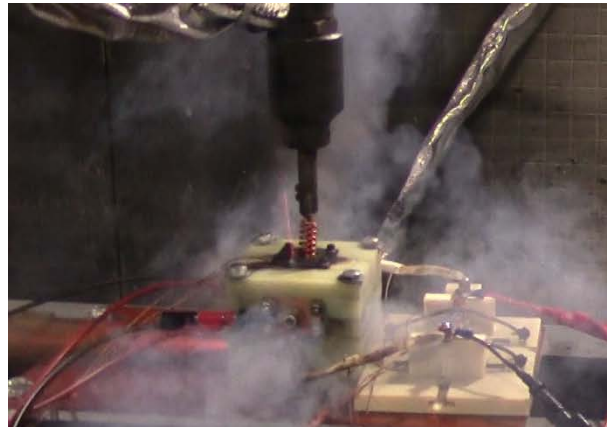


Cell #2 holder

Standard Setup



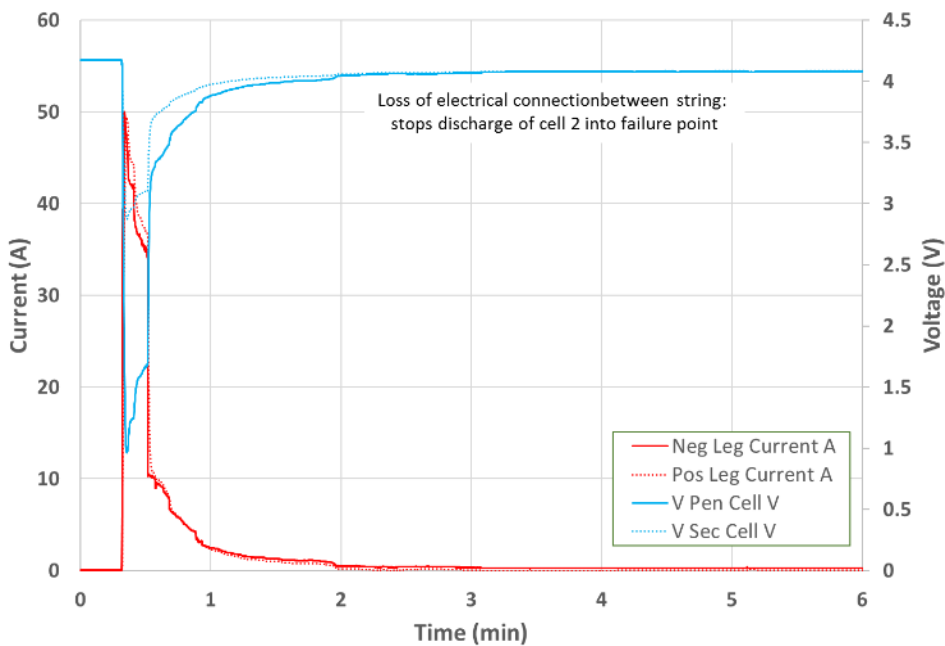
Improved Mechanical Contact



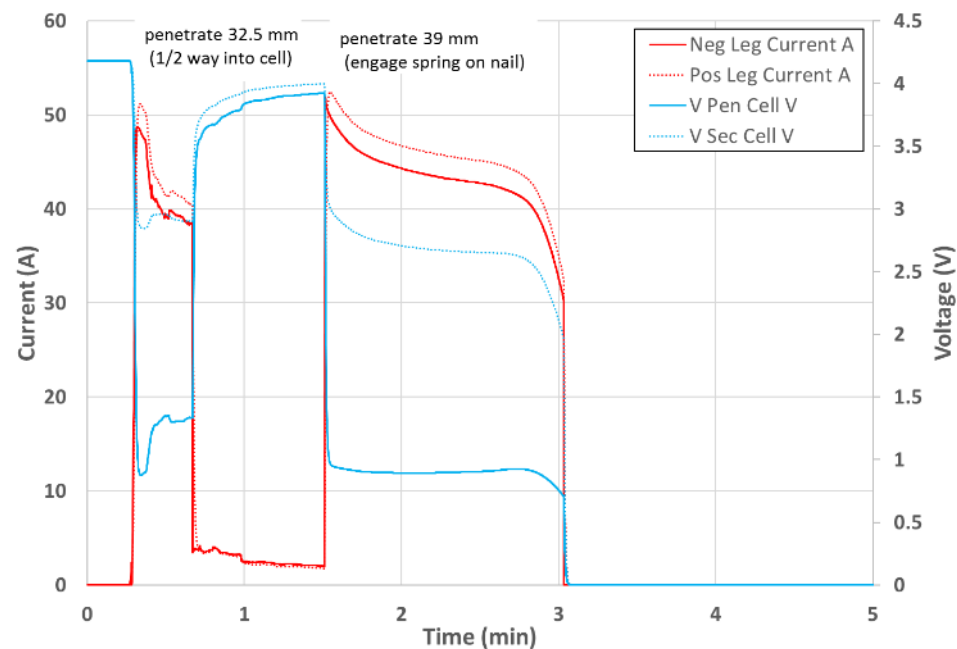
Short Circuit Current During Failure Propagation: NMC Sandia National Laboratories

Failures initiated by mechanical insult to cell 1 which is connected to cell 2 through constantan bridge wire

18650 NMC 3Ah cells – 1s2p



**18650 NMC 3Ah cells – 1s2p
Improved mechanical contact**

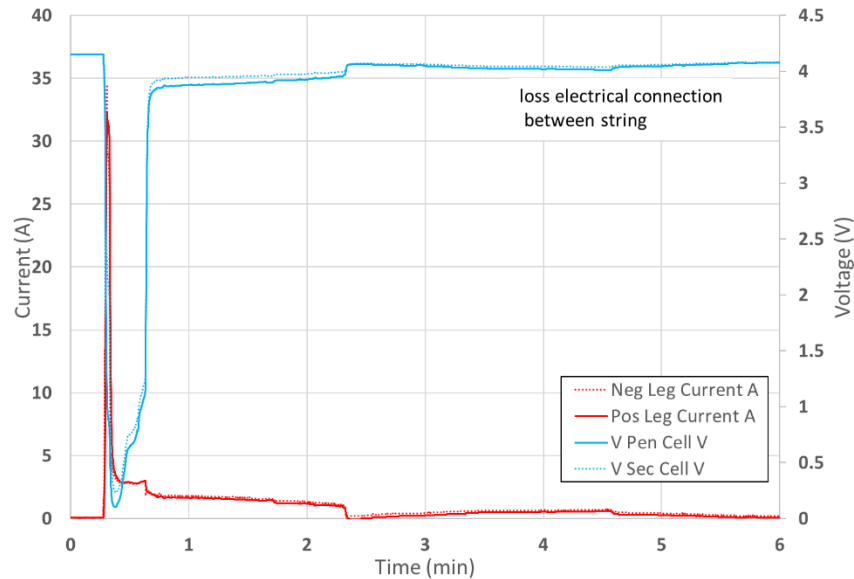


- **Peak currents across constantan bridge during failure propagation consistent between setups: ~50A**
- **Total energy discharged into cell 1 varies based on robustness on electrical connection allowing cell 2 to discharge into failure point longer: without spring 0.027 kJ (lost battery connection) and with spring 5.3 kJ**

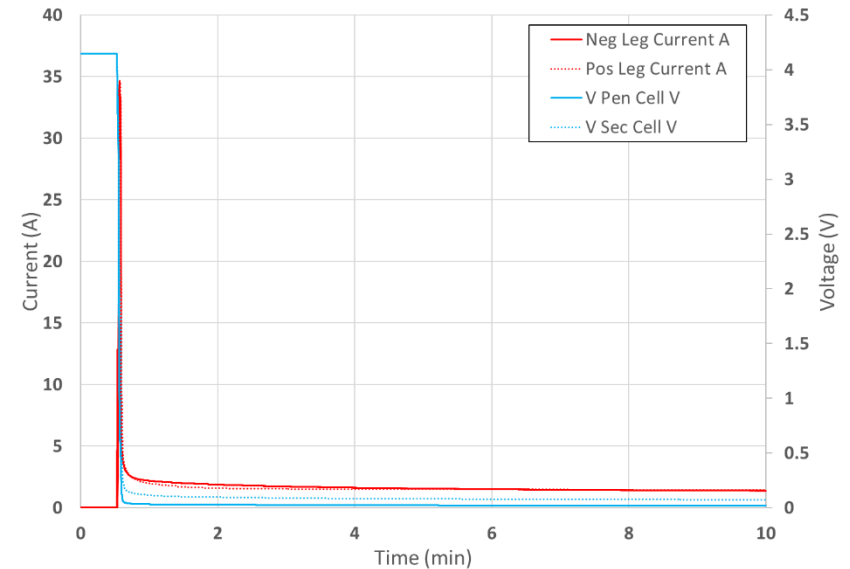
Short Circuit Current During Failure Propagation: NCA

Failures initiated by mechanical insult to cell 1 which is connected to cell 2 through constantan bridge wire

18650 NCA 3.1 Ah cells – 1s2p



**18650 NCA 3.1 Ah cells – 1s2p
improved mechanical contact**



- **Peak currents across constantan bridge during failure propagation consistent between setups: ~35A**
- **Energy output during discharge varies for two setups: without spring ~0.75kJ and with spring ~0.29 kJ (slow discharge of 1.5 A over 2 hours)**
- **Cell might contain a safety device making system become resistive during failure**
- **NCA cell not rated for high discharge currents (max DC is 2C)**

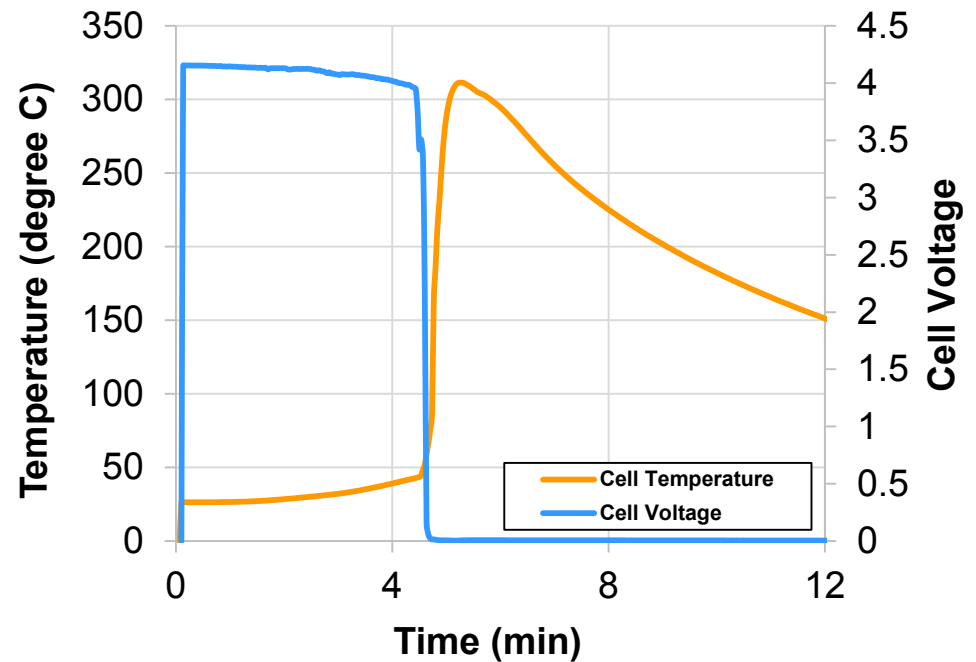
Chemistry comparison

Chemistry	Nominal Capacity (Ah)	Max rated discharge current for cell	Peak current during short circuit (A)	Total Energy discharged into Cell 1 (KJ)
LFP (18650)*	1.5	5.6A (3.7C)	37	14.9
LFP (26650)*	2.6	42A (16C)	30	15.0 (av)
LiCoO ₂ (18650)*	2.2	6.2A (2.8C)	90	2.94 (av)
NMC (18650)	3	20A (6.7C)	80	5.3 (spring), 0.027 (no spring)- lost battery connection
NCA (18650)	3.1	6.2A (2C)	35	0.29 (spring), 0.75 (no spring) <small>*Internal safety device might be preventing an external short current</small>

*testing presented at AMR FY16

- ***Although LFP is a more benign chemistry it is able to sustain a discharge much longer giving a higher total E out during discharge (KJ)***
- ***LFP able to sustain higher currents***
- ***Robustness of connection impacts ability to allow cell 2 to fully discharge into failure point***
- ***NCA has a 2C max discharge current while other cells tested are rated >3C***

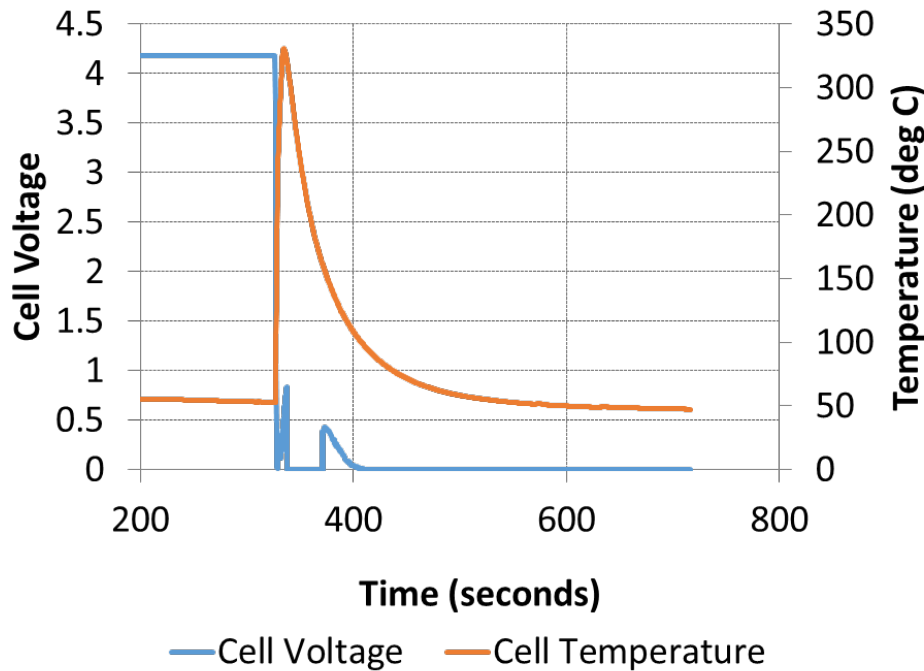
Alternative Methods to Simulate Internal Short Circuits: Laser Initiation



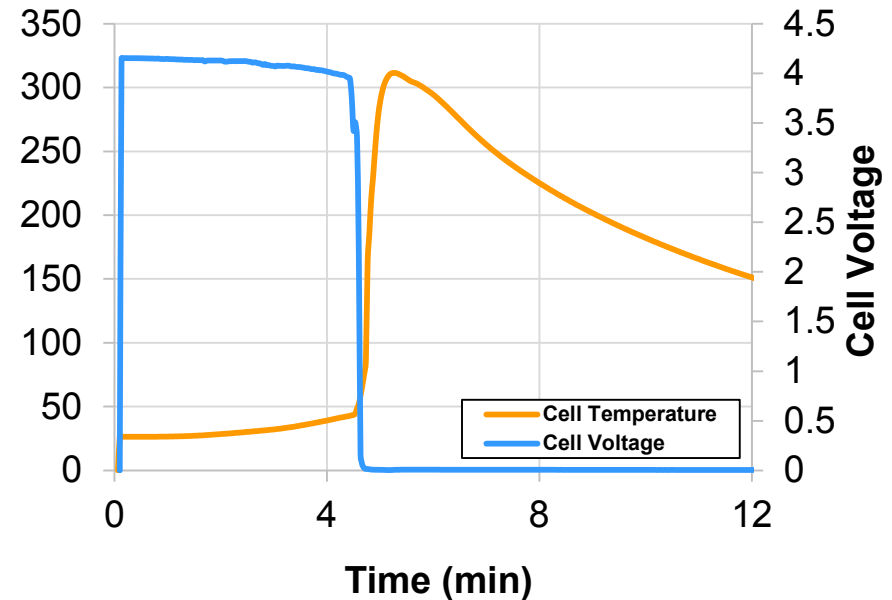
- Single cell failure initiated using 40W pulse laser
- ~38 J total energy needed for failure (20 1.9 J pulses)

Comparison to Mechanical Data

Nail Penetration Failure



Low Impedance Laser Induced Failure



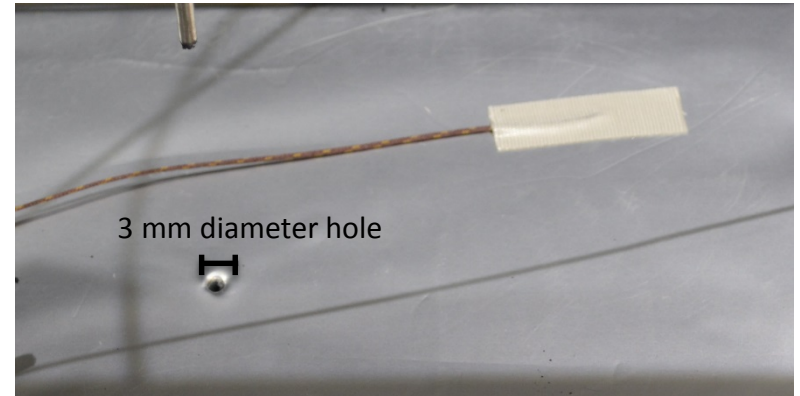
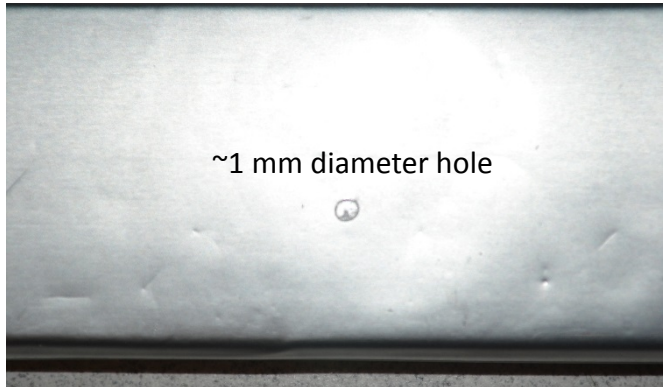
- Comparison of failure to nail penetration of same model of cell.
- Peak temperatures observed are similar, however the nail penetration shows much higher rate of failure after onset

Damage comparison: Laser vs. Nail

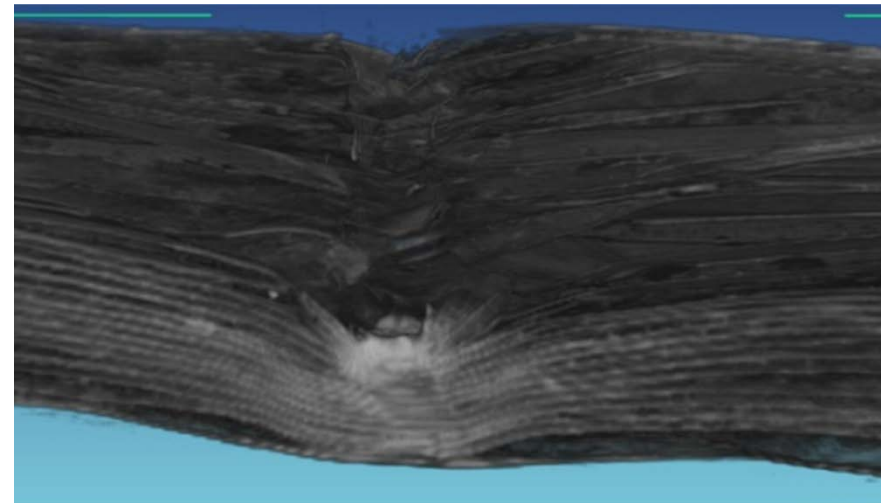
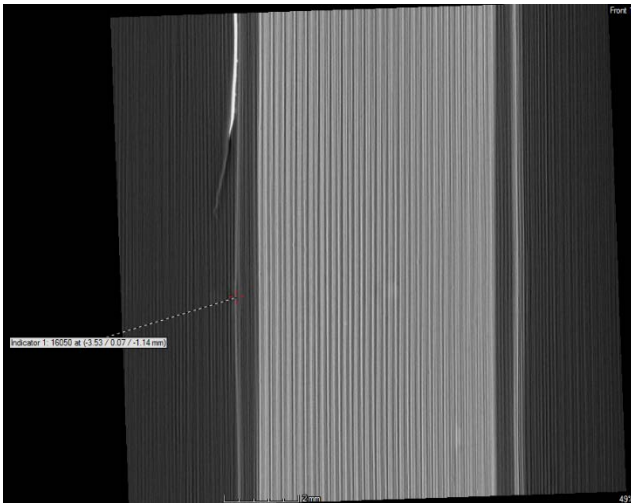
20 Pulse Laser

Blunt Rod

External



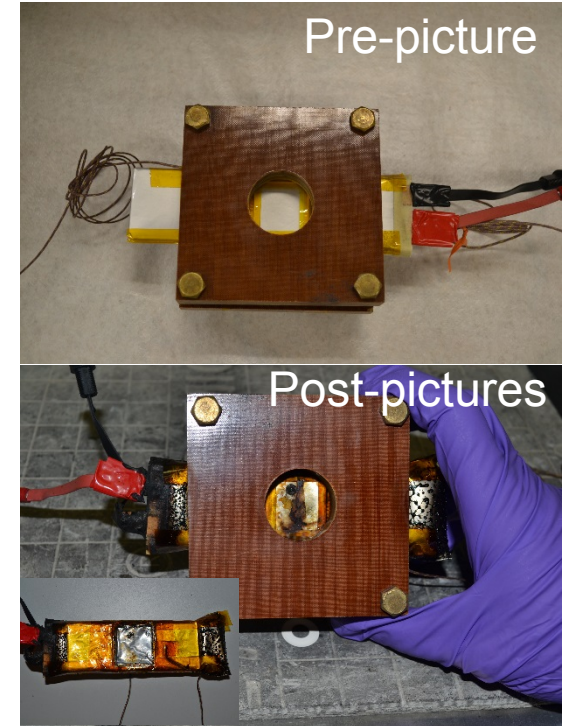
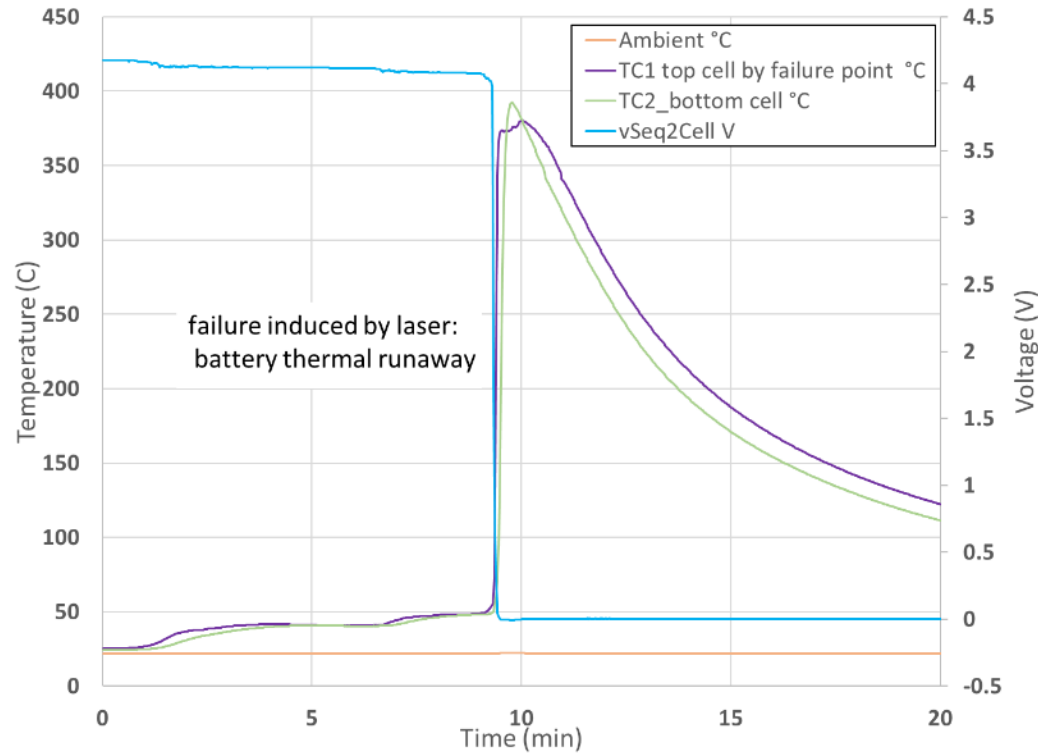
Internal



- Nail penetration shows significantly more internal damage.
- Internal damage done by laser initiation is very limited to surface layers.

Laser initiated failure through fused silica slide (2mm)

In hopes to reduce the oxygen exposure to hole being produced from laser, an IR transparent slide was used as barrier during testing

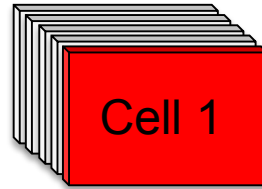


- Able to induce failure using laser through silica slide
- Final power setting of 350V, 20ms, 1Hz to induce thermal runaway
- Maintained seal between silica and pouch cell until full runaway
- *Follow on testing will be focus on experimental optimization (laser power, silica thickness, and improving air exposure at failure point).*
- *Technical Advanced has been submitted for laser induced battery failures*

Failure Propagation:

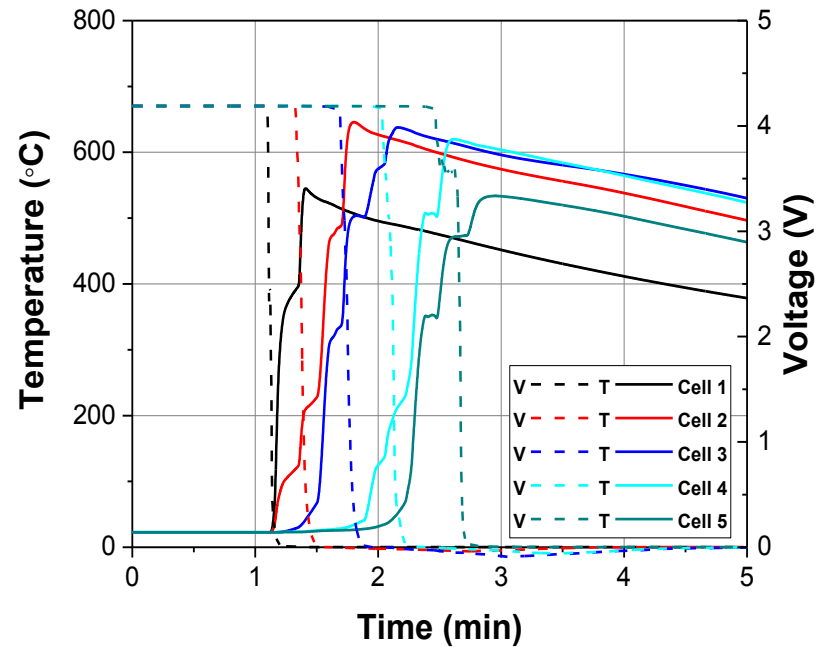
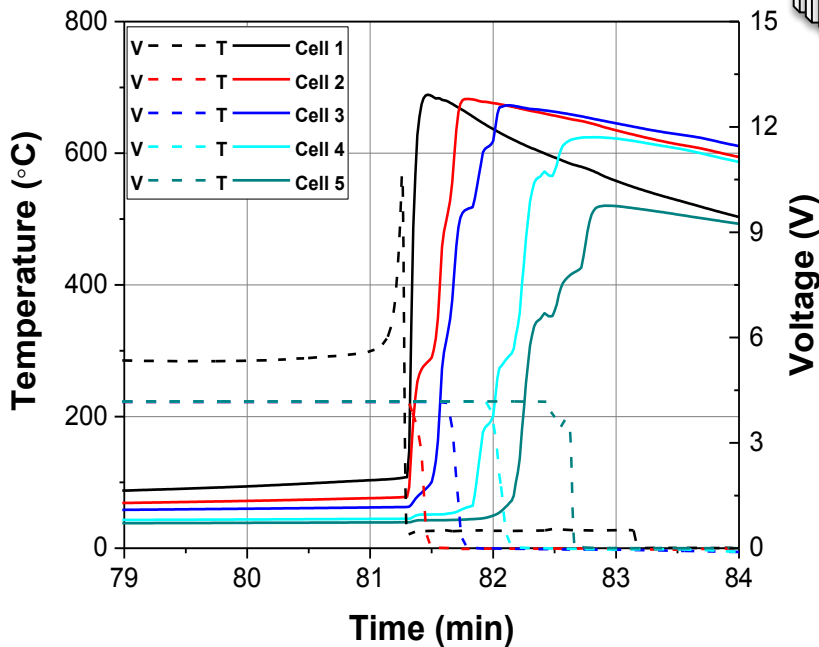
Alternative methods for failure initiation

Overcharge as failure mechanism in single cell to study propagation: Cell 1 overcharged at 1C rate until failure and propagation monitored



1C overcharge data

Nail penetration data



- *The overcharged cell failure more energetics than in nail penetration (faster heating rate) but did not impact the overall rate of propagation through the pack (in line with nail penetration)*
 - *peak battery temperatures are comparable for both testing methods*
 - *Complete propagation of all 5 cells was realized in both cases*
 - *Total time for propagation was ~1 min for overcharge and 1 min 20 sec for nail penetration*

Energy Injection Comparison Between Failure modes

Test	Energy Source	Conditions	Estimated Energy
20 Pulse laser	IR Laser	20 1.9 J pulses	38 J
Nail Penetration	Mechanical	20 mm penetration ~200 lb peak load	1.8 J
Thermal Ramp	Thermal	Heat to 200 °C	6300 J*
Overcharge	Electrical	1C to 200% SOC	43200 J**

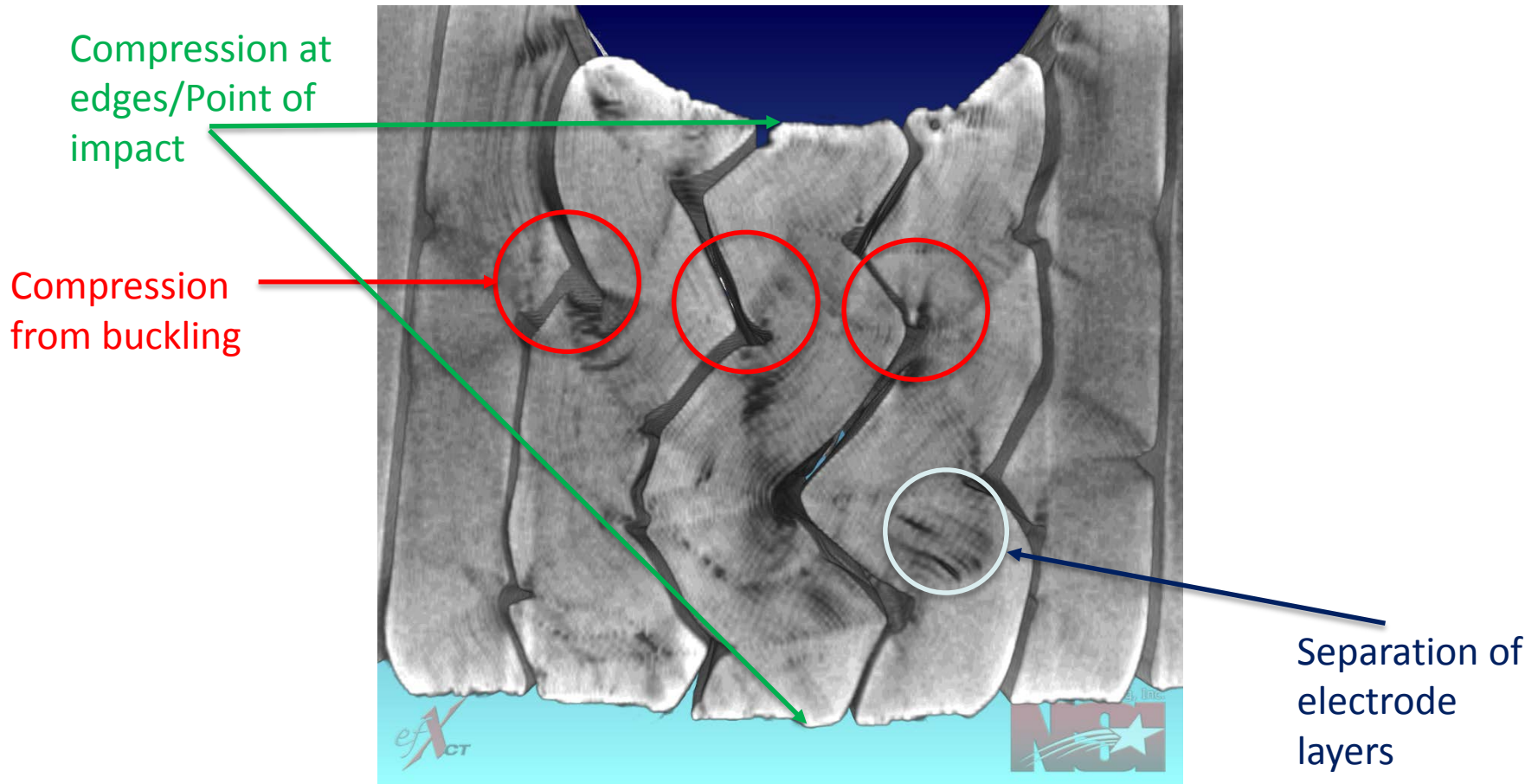
*Calculated for hypothetical 40g cell – larger cells will require more energy

** Calculated for a hypothetical overcharge at 3 A and 4 V at a 1C rate

- Energy comparisons show significantly less energy required for laser induced failure compared to overcharge/thermal ramp initiation
- However, more energy is required for laser induced failure when compared to nail penetration

Supporting CAEBAT Crash Worthiness

NREL/MIT Computer Aided Engineering for Batteries (CAEBAT) Program



- CT scan of a cylindrical impact into a discharged 12 cell string of cells.
- During the cylindrical impactation the cells experience both buckling and compression in some areas.
- Various avenues for cell failure can be observed.

USCAR-Battery Crash Worthiness/CAEBAT: Drop Tower /Impact Tester development



Specifications:

- Overall height: 14 feet (4.3 m)
- Drop Height: up to 10 feet (3.1 m)
- Drop Weight: 50 to 500+ pounds (22.7 – 226.8 kg)
- Max Impact velocity ~ 25.4 ft/s (7.74 m/s)
- Impact Force (assuming a 6" stopping distance): 10,000 lbs-f (44,482 N)
- Remote operation
- Data collection:
 - Displacement
 - Impactor velocity
 - Force at impact
 - Temperature
 - Voltage

Unit build to be completed in July 2017

Collaboration and Coordination with Other Institutions



- **Propagation and mechanical modeling through CAEBAT:NREL**
- **Post test analysis supporting ABR: ORNL and ANL**
- **USABC: INL, NREL, ANL, ORNL**
- **USABC Technical Advisory Committee (TAC)**
- **USABC Contractors**
- **USCAR Crash Safety Working Group (CSWG)**

Proposed Future Work

- Abuse testing cells and batteries for upcoming USABC deliverables and new contracts
- Propagation testing of batteries with increasing levels of design
 - passive and active thermal management
 - Complete analysis of short circuit current during failure propagation using larger format cells
 - Study effects of SOC on failure propagation
- Optimize laser induced short circuit failure mechanism
 - Testing with silica slide to seal penetration point
 - Extend testing into cylindrical cells
- Working with NREL refining a predictive failure propagation model
- Leverage system scale battery modeling effort at SNL to increase data for VTO portfolio
- Dynamic mechanical testing (implement new drop tester) and model validation to demonstrate battery crashworthiness (USCAR, NREL, CAEBAT)
- Support testing for post test analysis of cells to determine degradation mechanisms from cell overcharging: ORNL and ANL as part of ABR

Any proposed future work is subject to change based on funding levels.

Summary

- **Fielding the most inherently safe chemistries and designs can help address the challenges in scaling up lithium-ion**
- **Materials choices can be made to improve the inherent safety of lithium-ion cells**
- **Completed abuse testing support for all USABC deliverables to date and on track to complete all work by the end of FY17**
- **Developed a method to induce a battery short using a laser: TA filed on methodology/results**
- **Active thermal management in the form of spacers (Al and Cu) have a large impact on the extent of propagation.**
- **A method for measuring short circuit current during propagation was developed for 2 cell strings and a comparison between relevant li-ion chemistries has been made**
 - **Robustness of electrical connection effects the total energy output during the discharge**
- **Results for the mechanical testing of batteries will be used as input parameters for a crash worthiness model developed by NREL/MIT supported by CAEBAT. SNL will also provide validation test support when the model is complete.**
- **Design of dynamic drop tower complete with expected construction to be done by July 2017**
- **Testing support for post mortem materials analysis of 3 cell types has been completed in collaboration with ORNL and ANL**

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